EO-1 Technology Report for the LA-II Thermal Coating

August 16, 2001

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DOCUMENT CHANGE RECORD

REVISION	DESCRIPTION	DATE	APPROVAL
-	Initial Release		

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1.0 INTRODUCTION

The purpose of this technology demonstration is to verify the thermal performance of an improved white thermal control coating developed by AZ Technology, Inc. The thermal control coating referred to as LA-II, is a low absorptance inorganic white paint. A low absorptance thermal coating will allow radiators to run cooler when exposed to an UV environment providing improved performance for space radiators. Two flight calorimeters (Figures 1 and 2), built by Swales Aerospace, were flown on the Earth Observing-1 spacecraft to validate the performance of the AZW/LA-II low alpha inorganic white paint, using the known NASA/GSFC Z93P White Paint as a baseline for comparison.

Figure 1.0

2.0 TECHNOLOGY DESCRIPTION

Calorimeter (S/N 032) was coated with Z93P white paint by Grace Miller of Swales Aerospace and Calorimeter (S/N 033) was coated with AZW/LA-II low alpha inorganic white paint by Steve Jones of AZ Technology, Inc. Both coatings were developed by AZ Technology, Inc. Two flight thermistors were added to the EO-1 flight telemetry, TCALEXP1T for AZW/LA-II (S/N 033) and TCALEXP2T for Z93P (S/N 032).

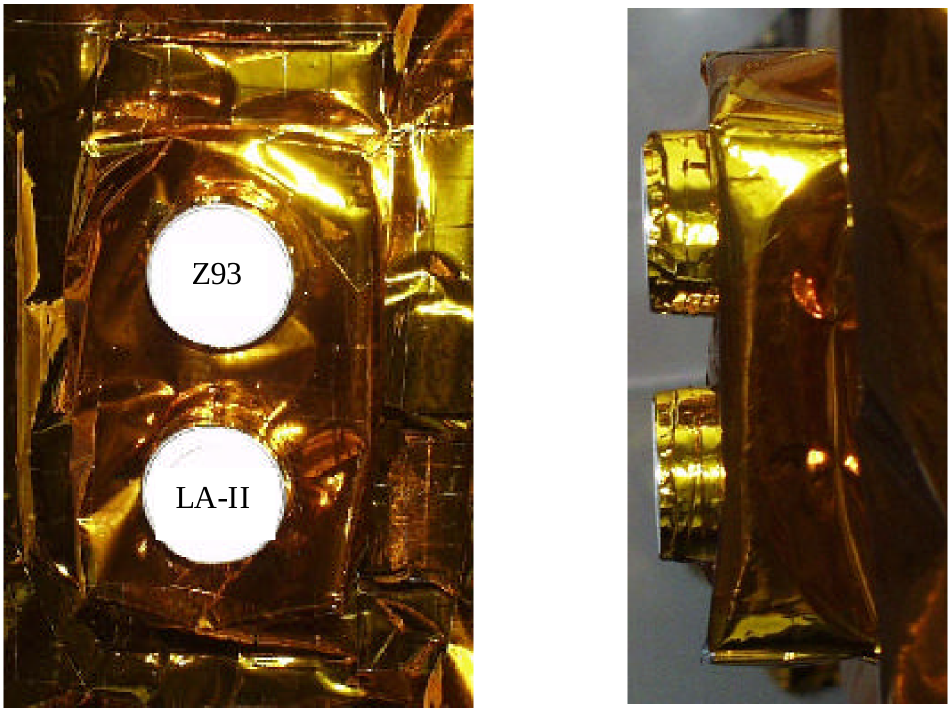


Figure 2.0

3.0 TECHNOLOGY VALIDATION

There are several key elements and requirements that must be identified and implemented properly to give merit to the technology validation of the LA-II white paint. These include:

- A clear view to space environment
- Thermal resistance (calibration) between calorimeter disc and spacecraft interface panel
- A minimum of 500 sun hours
- BOL measured thermal properties
- Contamination control through launch

Calorimeter Location

The calorimeters were mounted on a common aluminum bracket that set the *disc samples* above the radiator surface increasing the view factor to space and reducing inputs from other spacecraft components.

Figure 3.0

Calibration

The calorimeters were also calibrated prior to installation on the EO-1 spacecraft. This data will define a starting point for the degradation (if any) of the test samples. Parasitic conductive paths, while minimized with the Swales calorimeter, can never be completely eliminated. The sample disc is intended to read at a temperature based solely upon the radiative environment and the thermo-optical properties of the sensor disc. Due to these conductive influences the actual disc temperature is a balance between the environment and the housing temperature. Both calorimeters (Z93 and LA-II) were calibrated (Table 3.0.1) to provide a relationship between the recorded values and the theoretical values.

Calorimeter S/N	Housing Temp, °K	Sensor Disc Temp, °K	Shroud Temp, °K	Conductance Housing – W/sq.in-°C
#32 (Z93)	280	189	123	.000309
#33 (LA-II)	280	198	123	.000429

Table 3.0.1

Sun Angle

The total sun hours that the coatings are exposed has the largest influence on the rate of UV degradation. Experience indicates that measurable UV degradation of similar coatings occurs after a minimum of 500 equivalent sun hours. The EO-1 calorimeters have an orbit average sun angle of about 20° in a 66% suntime orbit. The total equivalent sun hours from 11/21/00 through 6/21/01 can be computed by the following:

Total Sun Hours = 212 day x 24 hour/day x .67 orbits/hour x sin 20° x 0.66 = 765 hours

BOL Optical / Thermal Properties

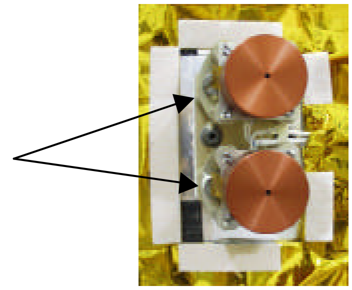
The Beginning of Life (BOL) properties for the Z93P control coating and the LA-II technology coating are shown in Table 3.0.2.

DESCRIPTION	Solar Absorptance, α_S (BOL)	IR Emittance, ε_H (BOL)
Z93P (S/N 032)	.17	.87
AZW/LA-II (S/N 033)	.11	.86

Table 3.0.2

Contamination Control

It is imperative that the thermal coating properties remain clean throughout the integration process prior to launch. The test samples are very small, and therefore, a small amount of contamination can have a large effect on the optical/thermal properties of the disc samples. The EO-1 calorimeters were fitted with a protective shield (Figure 3.5) to aid in protecting the samples through I&T and on the launch pad.



3.1 GROUND TEST VERIFICATION

The flight calorimeters were not included in the spacecraft level thermal vacuum test. However, the thermistors and representative mass hardware were included. The solar absorptance and IR emittance for each calorimeter samples was measured prior to integrating onto the EO-1 spacecraft. The measured values are shown in Table 3.0.2.

The calorimeter bracket hardware (Figure 3.0) is mounted on an EO-1 equipment bay panel, Bay 4 (Carbon/Carbon Radiator Panel). The panel thermal model with the bracket was tested during TV testing.

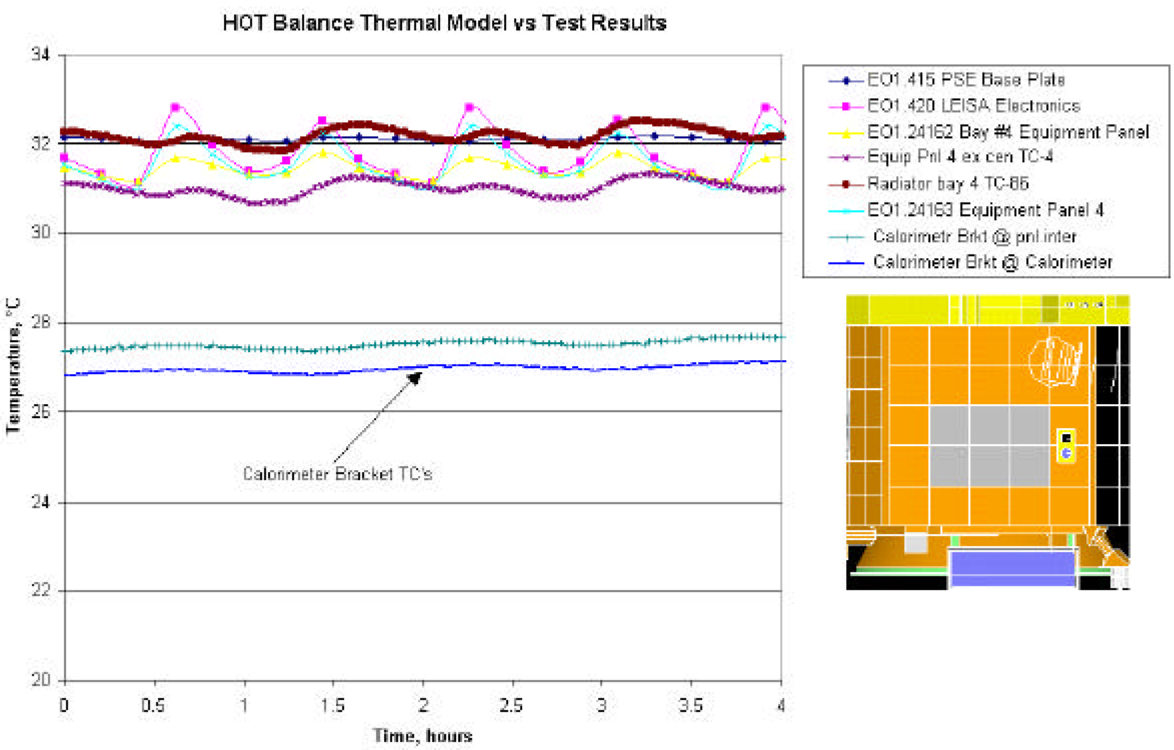


Figure 3.1

The gradient between the calorimeter bracket and Bay 4 equipment panel was successfully correlated to the four degree gradient that is observed in the data from the HOT thermal balance test. However, this trend cannot be verified by flight data since there are no corresponding flight thermistors for the bracket interface to the Bay 4 panel.

3.2 ON-ORBIT TEST VALIDATION

Two thermistors, TCALEXP1T and TCALEXP2T, were allocated to the EO-1 telemetry system to monitor the temperatures of the flight calorimeters. Originally, no specific tests were planned for the calorimeters.

However, the success of EO-1 to quickly obtain its mission goal provided opportunities for additional test validation. On June 21, 22, 23 and 24, 2001 the EO-1 spacecraft maintained a solar inertial attitude for the calorimeters during 25 minutes of the sunlit portion of the orbit, providing additional data points for validation. Figure 3.2 shows the results of these tests.

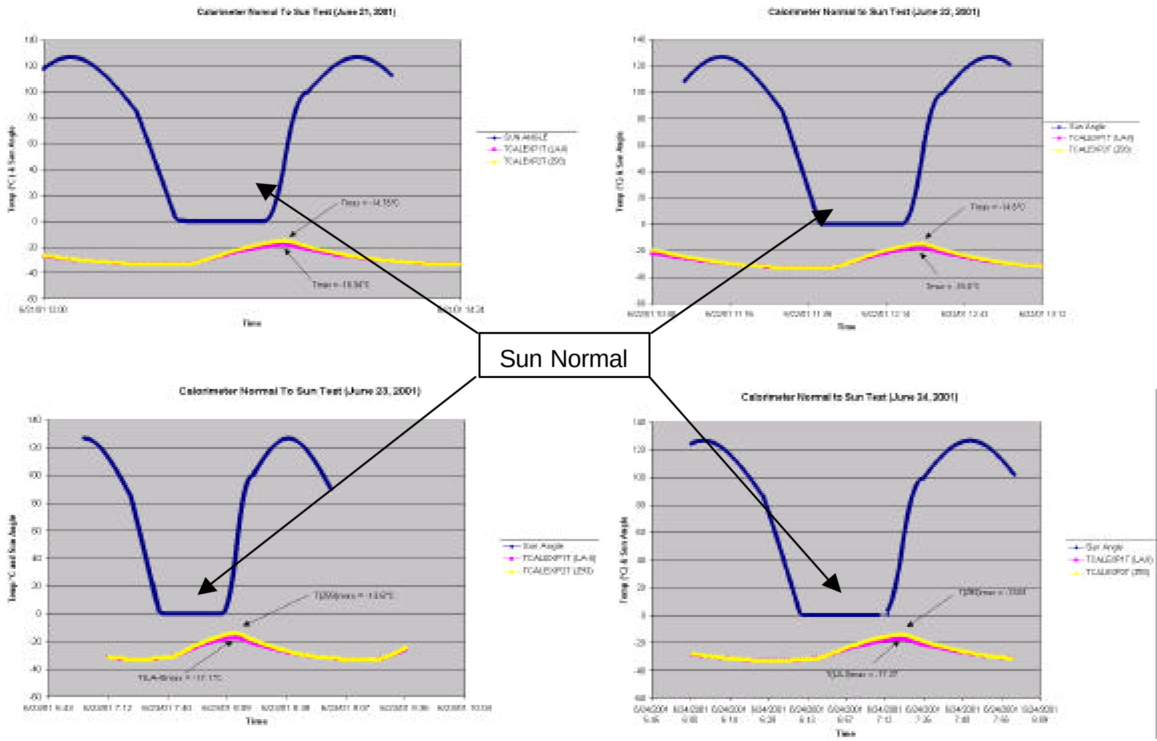


Figure 3.2

The plots shown above are taken from the on-orbit flight tests and provided significant data points for evaluating the optical properties of the Z93 and LA-II calorimeter disk samples. The dark blue line indicates the sun angle with respect to Bay 4, which is the spacecraft panel where the calorimeters are mounted. When the sun is directly normal to the disk samples the sun angle is zero. It appears from this data that the calorimeter samples don’t reach steady-state temperature. This information will be used to define the on-orbit test durations for any additional sun-normal flight tests.

3.2.1 Overview

The flight data from November 21, 2000 (launch date) to June 24, 2001 shows several consistent trends for the calorimeter thermistors and the Bay 4 panel thermistors from which reliable conclusions can be drawn. The calorimeter SINDA model was correlated using modified linear conduction couplings and modified panel material properties (thermal conductivity). The model predictions for the calorimeter disk samples and Bay 4 panel thermistor maximum temperatures are within 1 degree of those observed in flight data. Additionally, the model predicts panel gradients that are consistent with the trends observed in the flight data. The predicted minimum temperatures are 2-3 degrees (and for one thermistor, 5 degrees) within those of the flight minimum temperatures for the calorimeter disks and Bay 4 panel thermistors.

The change in maximum temperature for the calorimeter disks is resultant of either seasonal variations or a slight degradation in optical properties for the Z93 and LA-II paints. Although the case appears slightly stronger for the cause to be seasonal variations, for reasons I name below, no definitive claim can actually be made for either case at this time.

It is difficult to produce a conclusive analytical assessment of the level of degradation that the calorimeters have experienced. EO-1 had a limited number of thermistors available to accommodate the calorimeter technology demonstration and the location of the flight thermistors used to correlate the thermal model predictions are not located at the most desirable locations. Therefore, any model correlation must unavoidably use “subjective” values in order to produce predictions that are consistent with the flight data. Additional flight data collected over a longer time period is required to make any definitive conclusions of changes to calorimeter sample optical and/or material properties.

It appears that the calorimeter disks do not get sufficient UV exposure to noticeably degrade the paints. Several NASA publications on Z93 degradation report an EOL alpha in the range of 0.30 to 0.36 for LEO applications. As stated in Section 3.3, the 765 sun hours should provide enough UV exposure for LEO missions to begin exhibiting EOL trends for optical properties. Therefore, one would expect to see a greater indication of degradation from the flight data, but the data does not show a trend of warmer temperatures for the Z93 disk. If the solar absorptance, α, of Z93 is set consistent with the NASA information, the model predicts a maximum temperature of approximately –8°C (alpha = 0.30). This is 8°C warmer than any of the maximum temperatures reported in the flight data for this disk, and therefore, implies that no appreciable degradation has occurred.

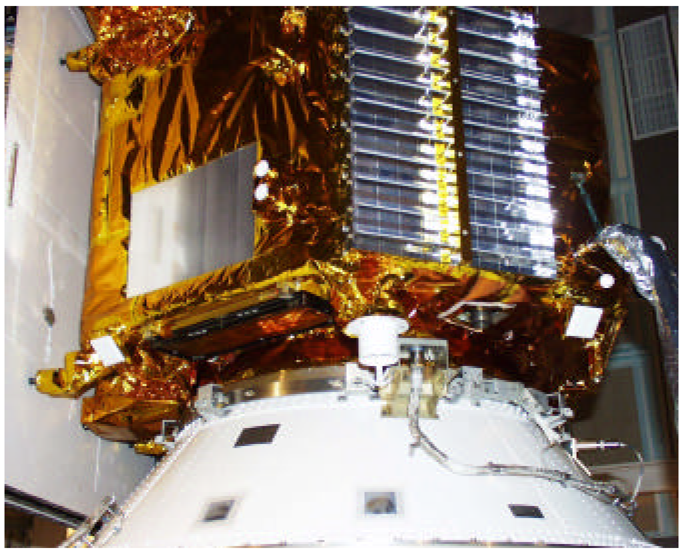


Figure 2.3.1: EO-1 Spacecraft at Launch Pad – Calorimeter Final Closeouts prior to Launch

3.2.2 Technology Verification Approach

The following is the approach taken to analytically verify the flight results and provide and engineering and physical assessment of the calorimeter flight data.

- Analyze the flight data for period November 21, 2000 through June 24, 2001 and note observable trends
- Correlate SINDA model to predict the temperatures and trends observed in the November and December flight data using one set of environmental conditions and only the BOL optical properties
    - Re-calculate the thermal conductivity of the Bay4 panel based upon the trends noted for thermistors TRADCC2T, TRADCC3T, TRADCC4T, TRADCC5T, and TRADCC6T.
    - Re-calculate the resistance through the honeycomb core of the Bay 4 panel based on the trend noted for thermistors TBAY4T and TRADCC4T.
    - Calculate a resistance to correlate the SINDA model to predict the trend in panel gradient observed in the data collected from the thermal balance tests
    - Use the calibrated h value obtained from the Calorimeter Thermal Vacuum Test Report (dated: March 3, 2000; author: John Winchester) for Z93 and LA-II
    - Make assumptions for unknowns in environmental conditions, panel gradients, calorimeter bracket temperatures, etc. (see below)

- Analyze cases using different combinations of environmental conditions, BOL optical properties, and EOL optical properties. Eight cases have been identified.
    - Select 2 sets of values for solar constant, albedo, and Earth IR to represent winter and summer environmental conditions.
    - Use provided BOL properties
        - Z93: alpha = 0.17, hemispherical emissivity = 0.87
        - LA-II: alpha = 0.11, hemispherical emissivity = 0.86
    - EOL properties
        - Degraded alpha Z93 only; emissivity unchanged
        - Degraded alpha for both paints; emissivity unchanged

3.2.3 Model Correlation

The data provided:

1. Flight data for November 21, 2000 to June 24, 2001 for 8 thermistors
    a. Z93 calorimeter disk (TCALEXP2T)
    b. LA-II calorimeter disk (TCALEXP1T)
    c. Bay 4 panel external side (TBAY4T)
    d. Bay 4 panel internal side (TRADCC2T through TRADCC6T)
    e. Bay 4 sun angle (for much of the time period)
2. BOL optical properties for Z93 and LA-II
3. Material properties for the paints and carbon-carbon composite
4. Calibrated h value for the calorimeters
5. Thermal balance test data
6. Electronics box power dissipations
7. Altitude and orbital inclination of EO1

The unknowns are:

1. Environmental conditions (solar constant, albedo, Earth IR, and Beta angle) for any given day of flight data
2. Degradation in emissivity
3. Temperature of the calorimeter bracket
4. Temperature of the Bay 4 panel underneath the calorimeter bracket
5. Temperature of the calorimeter cups
6. The dimensions of the flight calorimeter disks
7. Panel gradient in the external side of the Bay 4 panel

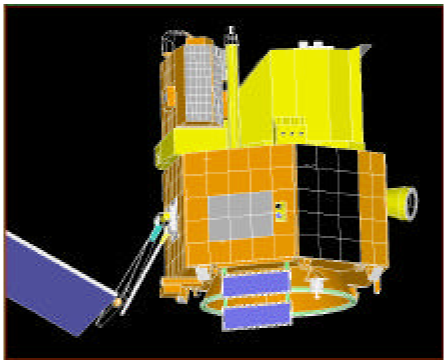


Figure 3.2.3: EO-1 Thermal Synthesis System (TSS) Geometric Math Model

Boundary conditions and analysis constants are listed in Table 3.2.3. Additional assumptions made are as follows:

1. Since it is known that the sun intensity is greatest during winter solstice (December/January timeframe) and lowest during summer solstice (June/July timeframe), lower-than-average values for the ranges of solar constant and Earth IR are used. A higher-than-average value for the range of albedo is used.
2. Since the emissivity for both paints is already very high and close to 0.90, the value for emissivity is not changed for either paint.
3. According to the calorimeter thermal vacuum test report (March 3, 2000--J. Winchester), the conduction coupling between the calorimeter cup and the calorimeter disk is extremely small. Therefore, the heat input from the cup to the disk is assumed to be negligible, and is ignored.
4. The temperature of the calorimeter disks after the "sun exposure experiment" (when Bay 4 sun angle is 0 degrees for one orbital period) is the temperature most likely to indicate degradation in absorptivity. The flight data selected for model correlation is from Day June 24, 2001 after 07:13:00.
5. The dimensions of the calorimeters are taken from the TSS model, cc_cal.tssgm. (Radius of the disk = 1.9 cm)
6. Beta angle in the TSS orbit data is assigned the value of 30 degrees for all cases.
7. The re-calculated thermal conductivity that is based upon the in-plane panel gradients observed in the flight data for the 5 thermistors located on the internal side of the Bay 4 panel is applied to the external side as well.
8. The transverse (through the honeycomb) panel gradient observed in the flight data is assumed to be consistent throughout the panel.
9. The gradient observed between thermocouple TC-4 and the thermocouple located at the interface of the calorimeter bracket and the Bay 4 panel in the HOT thermal balance test data is assumed to be the gradient that would be observed in flight if thermistor data were actually available.

Optical Properties				
	Z93		LA-II	
	Alpha	Emissivity	Alpha	Emissivity
BOL	0.17	0.87	0.11	0.86
EOL-a	0.18	0.87	0.12	0.86
EOL-b	0.30	0.87	0.11	0.86

Model Correlation Cases	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Flight Data	11/21/00	11/28/00	11/28/00	6/24/01	6/24/01	6/24/01	6/24/01
Solar Constant	1351.4	1351.4	1400	1289	1289	1289	1400
Albedo	0.3	0.3	0.3	0.35	0.35	0.35	0.3
Earth IR	238	238	245	216	216	216	245
Optical properties	BOL	BOL	BOL	BOL	EOL-a	EOL-b	BOL
E01 Altitude	705 km	705 km	705 km	705 km	705 km	705 km	705 km
Orbit inclination	98 degrees	98 degrees	98 degrees	98 degrees	98 degrees	98 degrees	98 degrees
Beta angle	30 degrees	30 degrees	30 degrees	30 degrees	30 degrees	30 degrees	30 degrees

Table 3.2.3

3.2.4 Summary of Model Correlation Cases

3.2.4.1 *Case 1*

Uses the heat rate data provided in the originally correlated SINDA model to provide a baseline and basis for the model correlation that uses the re-calculated thermal conductivities. The planet/solar data used are average values. BOL optical properties are used. No adjustments have been made to the thermal conductivity of the Bay 4 equipment panel in the SINDA model. The predictions of this case are compared against the 11/21/2000 flight data. Correlation of maximum temperatures is very good. This case was designed as a way to compare the new model correlation with the results of the original model correlation that was done for early on-orbit verification.

3.2.4.2 *Case 2*

Uses the same parameters and that are used in Case 1, but the predictions are compared against the 11/28/2000 flight data for a comparison with the results obtained from Case 1. The correlation of the maximum temperatures is good for this case, but poor in the correlation of the minimum temperatures.

3.2.4.3 *Case 3*

Draws the conclusion that the reason Case 1 and Case 2 predictions do not correlate more closely with flight data is perhaps due to different material properties actually exhibited on orbit. A re-calculated thermal conductivity that is based on the trends identified in the flight data is used in the SINDA model. In this case, it is also assumed that the late November season is more like winter environmental conditions, and adjusts the planet/solar data accordingly. BOL optical properties are used. The predictions are compared against the 11/28/2000 flight data. The correlation to maximum temperature is very good, and reasonable for the minimum temperatures. Moreover, the panel temperatures and gradients predicted correlate very well with the 11/28/2000 flight data. Therefore, it is then assumed that the adjustments for thermal conductivity are appropriate. Additional information is provided in the CC Radiator technology verification report.

3.2.4.4 *Case 4*

Makes the assumption that the June season is more like the summer environmental conditions, and adjusts the planet/solar data accordingly. BOL optical properties are used. The predictions from this case are compared to the June 24, 2001 flight data, and then to those predictions obtained from Case 3. The model correlation appears to be consistent. It would then appear from these results that the changes in maximum temperatures observed in the flight data are due to seasonal variations.

3.2.4.5 *Case 5*

Uses the same environmental parameters used in Case 4, but assumes a very slight degradation in optical properties for both paints. These predictions are compared to the June 24, 2001 flight data, and then to those predictions obtained from Case 4. The model correlation appears better than Case 4 for the maximum temperatures, but not as good as Case 4 for the minimum temperatures. On the surface, the results appear to show that the changes in maximum temperatures observed in the flight data are due not only to seasonal variations, but also to a slight degradation in optical properties. However, since the correlation in the minimum temperature is not as good as that obtained in Case 4, it could be concluded that this is not actually the case.

3.2.4.6 *Case 6*

This case assumes summer environmental conditions with a degraded alpha for the Z93 (alpha = 0.30). BOL properties are used for the LA-II paint. The temperature predicted for Z93 is approximately 15 degrees warmer than is observed in the 6/24/2001 flight data.

3.3.4.7 *Case 7*

This case assumes that the environmental conditions for June are the same as for November / December timeframe with BOL optical properties.

Model Correlation Results				
	Maximum Temperatures			
	LA-II		**Z93**	
	Flight Data	**Predicted Temps**	**Flight Data**	**Predicted Temps**
Case 1	-23.55	-25.0	-22.2	-23.32
Case 2	-21.7	-19.14	-16.82	-15.71
Case 3	-21.7	-22.2	-16.82	-17.8
Case 4	-22.03	-23.67	-19.13	-20.94
Case 5	-22.03	-22.18	-19.13	-19.23
Case 6	-22.03	-27.4	-19.13	-7
Case 7	-22.03	-24.91	-19.13	-20.54
	Minimum Temperatures			
	LA-II		**Z93**	
	Flight Data	**Predicted Temps**	**Flight Data**	**Predicted Temps**
Case 1	-31.2	-30.7	-30.81	-31.66
Case 2	-34.39	-26.37	-33.37	-26.37
Case 3	-34.39	-30.9	-33.37	-30.8
Case 4	-33.37	-30.3	-33.37	-30.78
Case 5	-33.37	-29.36	-33.37	-29.63
Case 6	-33.37	-32.65	-33.37	-20.0
Case 7	-33.37	-30.55	-33.37	-28.74

Table 3.2.4

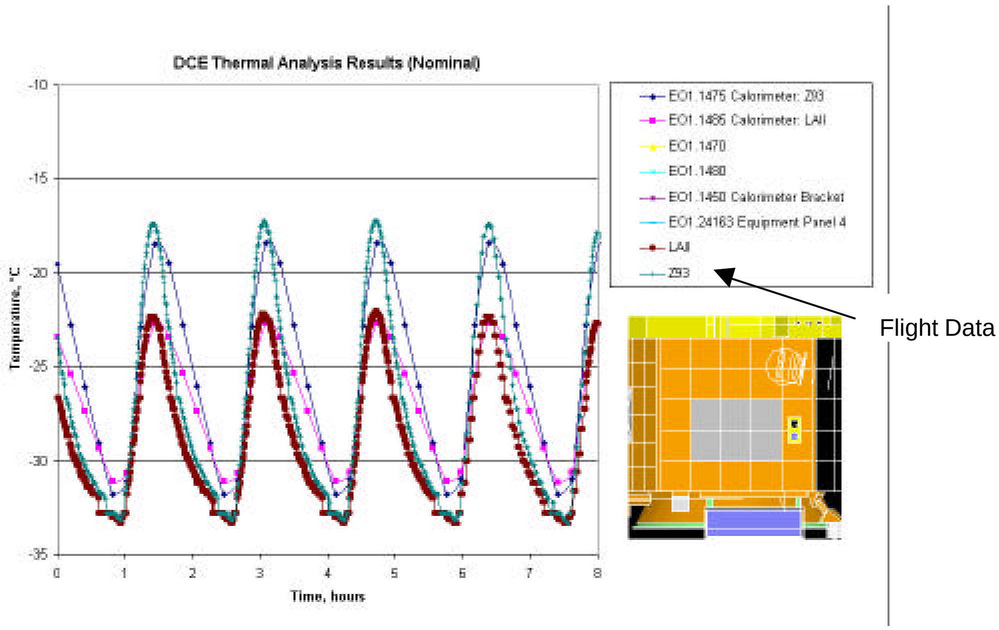


Figure 3.2.5

3.2.5 Observable Trends in the Calorimeter Flight Data

- The period of December 14, 2000 through February 14, 2001 appears to show a trend in calorimeter temperatures that would be observed for a Beta cycle at this altitude (705 km) and inclination (98 degrees), except that the timeframe appears too short for a complete cycle in Beta angles. Furthermore, the trend is not repeated after February 14, 2001----the temperatures gradually decrease (possibly due to change in seasons) until the "sun exposure experiment" is run (June 22, 2001). This data would indicate that there are additional variables that are influencing the temperatures of the calorimeter disks, which have not been considered in the model correlations. It is unexplainable with the current set of data.
- The slope of the temperature change observed during the "sun exposure experiment" is greater for the Z93 disk.
- It appears that neither calorimeter reached steady-state temperatures during the "sun exposure experiment".
- The Z93 disk is consistently warmer than the LA-II disk, as would be expected.
- The gradient between the maximum temperatures of the two calorimeters is consistently 5-6 degrees.
- The gradient between the minimum temperatures of the calorimeters is consistently approximately 0.2 degrees.
- The LA-II disk average temperature (- 29 degrees C) does not appreciably change when comparing the data from the beginning of the mission to the data from June 24, 2001.
- The Z93 disk average temperature decreases from approximately –27 degrees C at beginning of mission (December) to approximately –28 degrees C in June.
- Maximum orbital temperatures occur when Bay 4 sun angle is approximately between 63 degrees and 70 degrees.
- Minimum orbital temperatures occur when Bay 4 sun angle is approximately between +24 degrees and +30 degrees.

A summary of the flight data for Z93 and LA-II are shown in Figures 3.2.5.1 and 3.2.5.2. The figures represent data taken from November 21, 2000 (launch day) through June 24, 2001. The minimum, maximum and time weighted average temperatures are from a single 24 hour period from each from launch day.

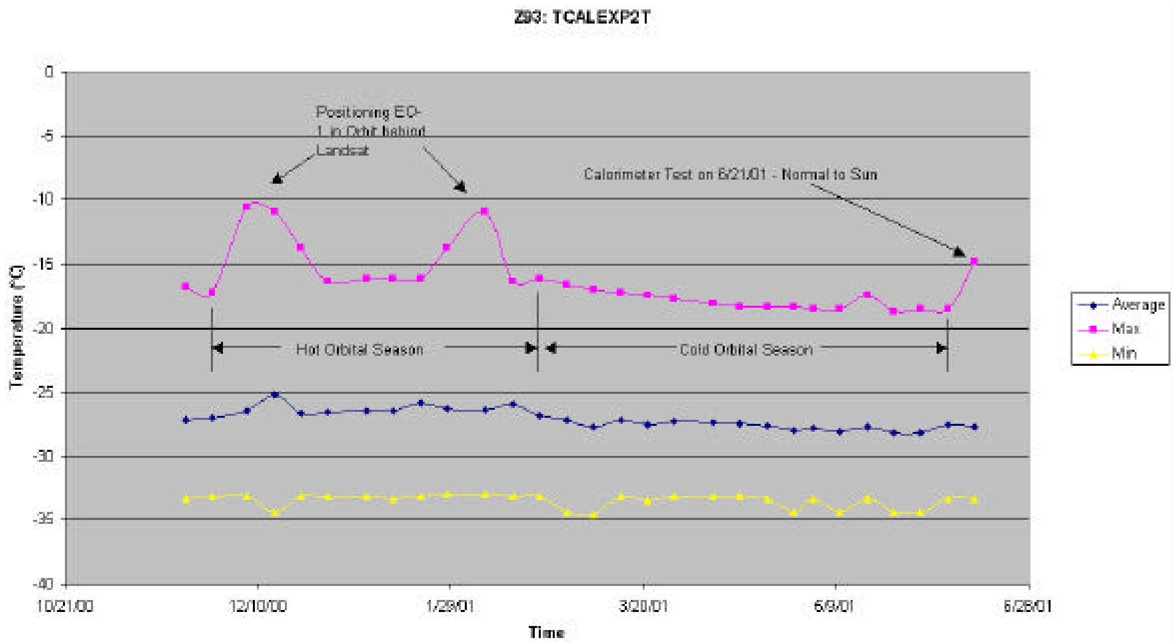


Figure 3.2.5.1

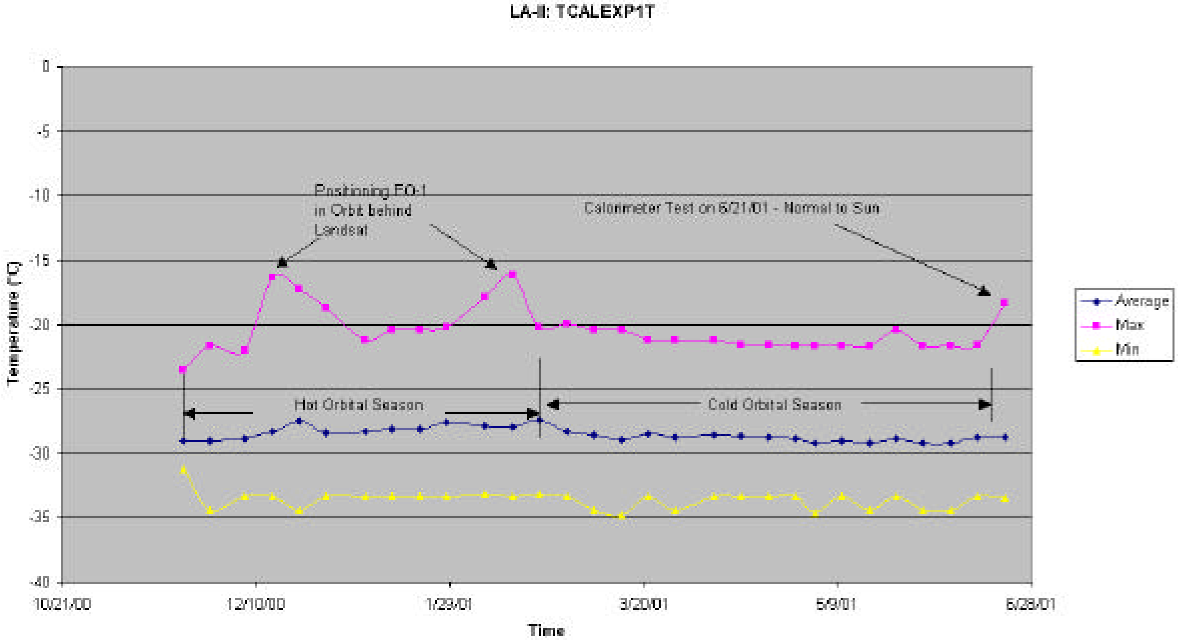


Figure 3.2.5.2

3.3 ON-ORBIT USAGE EXPERIENCE

The LA-II coating has shown no appreciable property degradation. However, additional calorimeter normal to the sun vector testing would allow for more data points and provide a more substantial number of sun hours or UV exposure on the LA-II sample. The LA-II coating is currently baseline for the NASA SWIFT mission as a radiator coating.

4.0 NEW APPLICATION POSSIBILITIES

The LA-II paint will be used as an external radiator thermal control coating by NASA/GSFC on the SWIFT spacecraft.

5.0 FUTURE MISSION INFUSION OPPORTUNITIES

The paint will be implemented on future missions as the requirements for specific missions are determined and the need arises.

6.0 LESSONS LEARNED

- LA-II optical properties verified maintaining stability with improved solar absorptivity vs. Z93
- LA-II may provide cooler radiator temperatures when exposed to UV: (Data shows 5°C cooler in UV)
- Follow calorimeters/samples through vibration testing. Extremely dirty environment that could contaminate thermal coatings–we flew the spare calorimeters
- Thanks to Dennis Hewitt at NASA/GSFC for his efforts in making the LA-II thermal coating a successful technology demonstration.
- New coating now available to flight projects: baseline for the SWIFT spacecraft.

7.0 CONTACT INFORMATION

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8.0 SUMMARY

The thermal model results correlate very well with the EO-1 flight data. However, a full 12 months evaluation and comparison of the calorimeter data should provide a definitive assessment of the new LA-II low alpha inorganic white paint. For this study the LA-II appears to remain as stable as the Z93 maintaining it's improved solar absorptance properties.

9.0 CONCLUSIONS

It's difficult to make any conclusive statement on whether the LA-II coating has seen any degradation. It is fairly certain that there is no substantial degradation based on such a small change in temperature over the six month on orbit data obtained for the calorimeters. Additional calorimeter normal to the sun vector testing would allow for more data points and provide a more substantial number of sun hours or UV exposure on the calorimeter samples. The plan is continue to evaluate the performance of the two paint samples to the end of the 12 months mission and provide an updated report to NASA/GSFC.

10.0 TECHNICAL REFERENCES

None.